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Ultrabroadband near-infrared pulse generation by noncollinear OPA with angular dispersion compensation

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Abstract A telescope-grating-deformable scheme is proposed to compensate the angular dispersion of ultrabroadband spectrum. A simple design consideration is formulated based on the large angular dispersion of the idler from noncollinear optical parametric amplification. A proof of principle experiment is demonstrated. A 3-μJ ultrabroadband near-infrared pulse with spectrum range from 700 to 1400 nm has been generated. The technique has great potential to provide an ultrabroadband seed with negligible angular dispersion for high-power amplification of few-cycle pulses.

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1 Introduction

By conventional laser-amplification technology, chirped pulse amplification (CPA) [1], very high power levels (petawatt) can be achieved, but the pulse duration determined by the laser material is limited to the tens-of-femtoseconds range. Therefore the accessible peak intensities of the produced pulses are confined well below the level needed for the investigation of high-field laser–matter interaction phenomena. However, in recent years the technique of optical parametric amplification (OPA), which does not suffer from this limitation and allows for very large amplification bandwidths, has opened up a new path towards generating ultrahigh-power, few-cycle laser pulses [2–14]. The OPA technology can be combined with CPA, allowing for high pulse energies by amplifying a temporally stretched pulse and subsequent compression. This scheme was firstly proposed by Dubietis et al. [15]. OPCPA systems have already been demonstrated to deliver pulse energies as high as 35 J in 84-fs pulses [16] as well as 90 mJ in the few-cycle regime (10 fs) [17]. However, the generation of joule-scale pulse energies in the few-cycle regime has yet to be demonstrated and constitutes the aim of the petawatt field synthesizer (PFS) [18] development.

At the heart of the PFS project lies the development of the novel short-pulse-pumped OPCPA scheme and its scaling to petawatt peak powers. Preliminary proof-of-principle experiments using the short-pulse-pumped OPCPA scheme have already been carried out recently at MPQ using the multiterawatt ATLAS Ti:Sapphire laser system [19]. In order to reach petawatt peak power, large aperture nonlinear crystals (KDP or DKDP) [20] have to be used at the high-power amplification stages to avoid the damage of the crystals. Considering the nonlinear crystals and high-power green pump lasers, the ultrabroadband near-infrared seed with spectrum range from around 700 to 1400 nm is severely necessary. Currently, one can easily generate an ultrabroadband pulse with spectrum covered from 500 to 900 nm or even broader by filamentation supercontinuum in noble gases and in hollow-core fibers. In this paper a noncollinear OPA is considered to shift an ultrabroadband near-infrared (NIR) pulse to the spectrum range from 700 to 1400 nm. The NIR pulse has large angular dispersion. A technique with telescope-grating scheme with 600 lines/mm grating was firstly demonstrated in Ref. [21] but with less design considerations inside. In this work the angular dispersion com-

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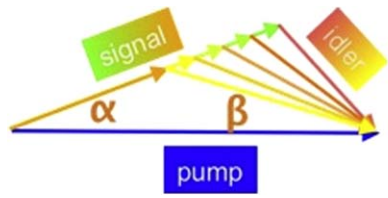

Fig. 1 Noncollinear geometry scheme of OPA

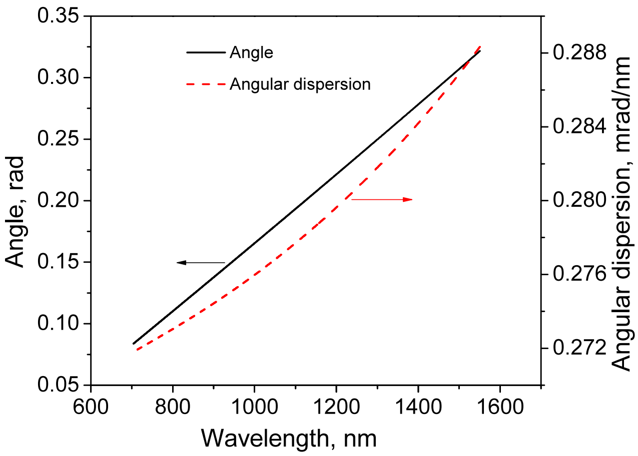

Fig. 2 Idler angle and angular dispersion generated from NOPA with BBO crystal pumped by 395 nm

pensation technique with telescope-grating scheme is formulated and developed, and experimentally demonstrated, which can also be used to compensate other angular dispersion in both linear and nonlinear range.

2 Design considerations

In optical parametric amplification a seed pulse is amplified by a three-wave mixing process in a nonlinear optical crystal, i.e., the energy is transferred from the narrowband pump beam into the broadband seed beam. In this process the conservation of momentum and energy leads to the spontaneous generation of a third beam, the idler. Since the amplification bandwidth only depends on the phase matching between the seed and the pump beams in a fixed nonlinear crystal, amplification can occur over a very large bandwidth. If noncollinear geometry is chosen, this phase-matching bandwidth can be extended even further [2, 4]. In addition to an ultrabroadband amplified seed pulse this results in an angularly dispersed idler beam, which is schematically shown in Fig. 1. For a fixed input noncollinear angle α, which is the angle between the signal and the pump beam, the output idler angles β are governed by (1) (written later in the text). $n_{1,i}$ and $\lambda_{1,i}$ are the refractive indexes in nonlinear crystals and the wavelengths of signal and idler beams, respectively. For experimental considerations, when frequency doubling of 800 nm is used to pump BBO crystals, the generated idler angles and angular dispersions at fixed typical noncollinear angle $\alpha = 3.7$ deg are shown in Fig. 2. For the interested spectrum range of 800–1400 nm, the angle difference is up to 10 deg. and the corresponding angular dispersion is 2.73–2.85 mrad/nm.

$$\beta = \arcsin\left(\frac{n_s\lambda_i}{\lambda_s n_i} \cdot \sin\alpha\right). \tag{1}$$

Among the general optical devices, gratings are most frequently used to control the angular dispersions. The angular dispersion of a collimated beam after grating can be given by (2) (later in the text). Normally first diffraction order ($n = 1$) is used d is the groove density of grating. γ and θ are the incident and the diffracted angles, respectively.

$$n\lambda = d\bigl(\sin(\gamma) + \sin(\theta)\bigr)$$

$$\Leftrightarrow \theta = \arcsin\left(\frac{\lambda}{d} - \sin(\lambda)\right). \tag{2}$$

With (1) and (2), (3) can be constructed in order to compensate the linear angular dispersion with grating.

$$\beta = m \cdot \theta + c. \tag{3}$$

Here m is the linear coefficient of angular dispersion, which can be functioned by the magnification factor of a telescope, c is a constant. Simply by nonlinear least-square fitting calculation between (1) and (2) one can obtain the optimum magnification factor of the telescope and the groove density of the grating for the spectrum range of interest. Note that the results are sensitive to the interested wavelength range to calculate. In the calculations, 700 to 1550 nm spectrum range has been considered for the interested region of 800 to 1400 nm.

For the idler with central wavelength of around 1100 nm and more than 600-nm spectrum bandwidth, the calculated optimum groove density of grating and magnification factor of telescope are around 230 lines/mm and 1.19, respectively. The linear angular dispersion can be compensated very well. The residual nonlinear angle difference is less than 10 μrad and the corresponding nonlinear angular dispersion is less than 0.04 μrad/nm as shown in the left column of Fig. 3. These results are two orders better than the one reported in Ref. [21]. Even for commercial 300 lines/mm grating and magnification factor of 0.912, the calculated results are also one order better, which are depicted in the right column of Fig. 3. The validity of the setup with less groove density grating has been tested by our ray-trace analysis. For the residual nonlinear angular dispersion a deformable mirror inserted in between the two mirrors of the telescope can be reasonable to compensate it well. Based on the design considerations with telescope grating plus deformable scheme one can easily compensate the angular dispersion in both linear and nonlinear regions.

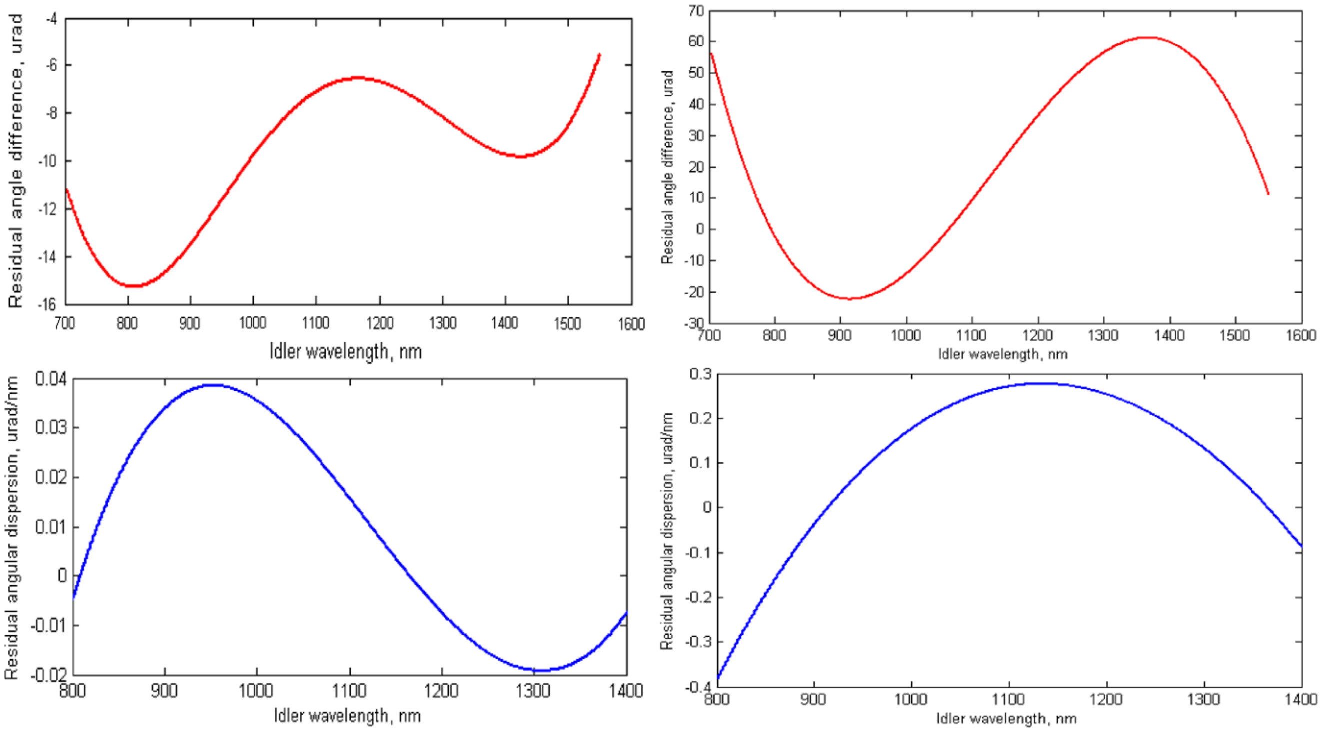

Fig. 3 Calculated optimum idler angular dispersion compensation of around 1100 nm central wavelength with 600-nm bandwidth: *left column* for optimum condition, *right column* for 300 lines/mm grating

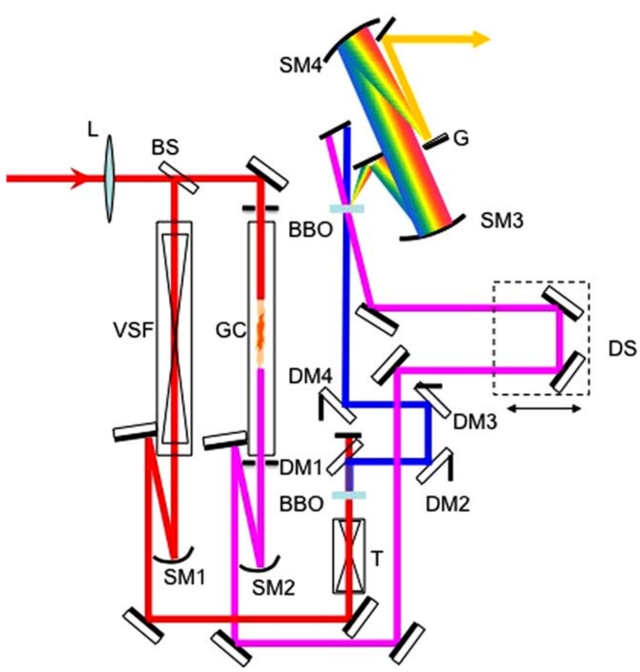

Fig. 4 Schematic experimental setup (see text for details)

3 Experimental demonstration

For a proof of principle experimental demonstration with 300 lines/mm grating, a beam with 1.4 mJ, 30 fs at 1 kHz from a modified Femtopower Pro was used. A schematic experimental setup is shown in Fig. 4. The beam after a focusing lens ($f = 1.5$ m) was divided into two parts by a 65/35 beam splitter: the reflected beam through a vacuum spatial filter was collimated by a spherical silver mirror with focal length $f = 1$ m. A reflective type telescope was used to change the beam size. After a thin BBO crystal (120 μm) cut for Type I frequency doubling and four dielectric coated mirrors with high reflectivity at 400 nm, which were used to cut off the fundamental beam, the blue pulse was used to pump NOPA; the transmitted pulse experienced the spectrum broadening in 2 bars argon gas by filament. An iris was used to select the central part of the single filament. After collimation by a spherical silver mirror ($f = 1.25$ m) and a delay line, the white light was seeded in NOPA. With internal noncollinear angle around 3.7 deg., 500 μm Type I BBO crystal an idler with large angular dispersion has been generated. The idler was first guided by a silver-coated plate. After an imaging telescope consisted with two 2-inch spherical silver mirrors (ROC = 400, 365 mm), the angular dispersion was collimated by a 300 lines/mm grating. The compensated idler was picked out by another silver mirror.

The typical spectrums for the pump, seed, and compensated idler are shown in Fig. 5a measured with EPP2000. The longest wavelength of compensated idler can reach up to 1400 nm as shown in Fig. 5b recorded by AvaSpec-NIR256-1.7. The low intensity at the longer wavelength

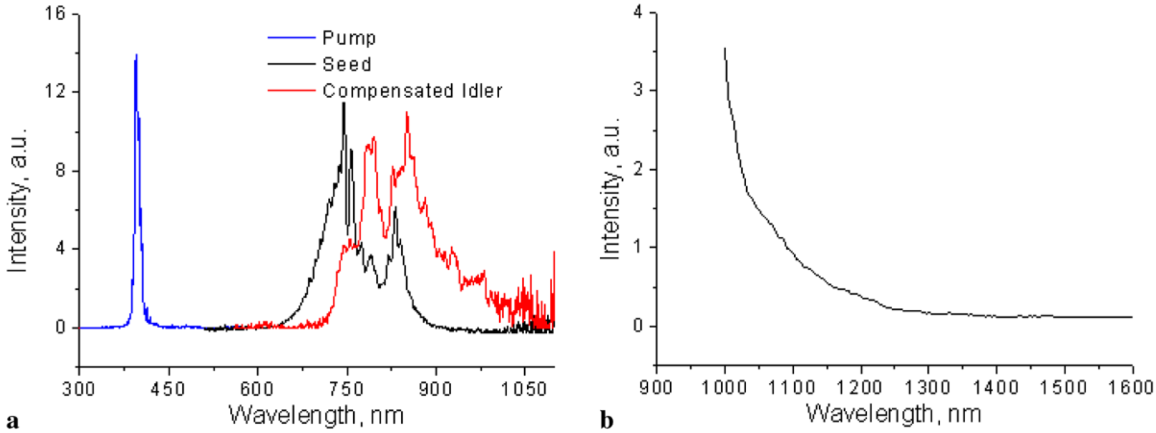

Fig. 5 Typical spectrums of pump, seed, and compensated idler

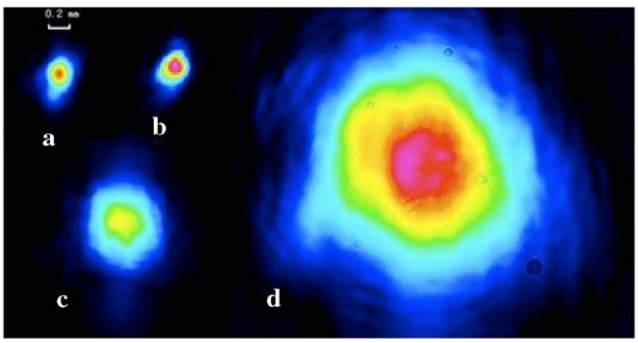

Fig. 6 Beam profiles of seed and compensated idler (see text for details)

range of the idler is due to the low intensity of shorter wavelength of the seed. It can be concluded that with the seed from hollow-core fiber, the intensity at longer wavelengths can be improved dramatically. Beam profiles of seed and compensated idler are depicted in Fig. 6. Figure 6a is the seed beam profile at the focus. Focus compensated beam profile with 12.5 mm lens is depicted in Fig. 6b. Near-field and 1-m far-field beam profiles are shown in Fig. 6c and Fig. 6d, respectively. Based on the beam profiles, the collimated idler is good enough for further amplification. Pulse energy after compensation is recorded to be more than 3 μJ. There are several technologies to increase pulse energy and further decrease angular dispersion, such as pulse-front matching between the pump and the seed [19], using the seed from hollow-core fiber, optimizing the pump beam profile, employing the higher efficiency grating and deformable mirror in compensation setup. More than several tens μJ ultrabroadband NIR pulses with negligible angular dispersion can be expected under the same conditions.

4 Summary

In this work a technique with telescope grating plus deformable mirror is proposed to compensate both the linear and the nonlinear angular dispersion. Simulation data confirm it as an effective tool to collimate the angular chirp pulses. A simple detail design consideration has been formulated. The method can be used to compensate other angular chirped pulses. In a proof of principle experiment, an ultrabroadband 3-μJ NIR pulse with spectrum range from 700 to 1400 nm and good beam profiles has been generated by NOPA with angular dispersion compensation, which has a great potential application on the amplification of few-cycle pulses with negligible angular dispersion.

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